On Certain Aspects of Utility Fog

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An example of the unusually powerful inventions possible with atomic precision molecular manufacturing

He thought he saw an Elephant, That practiced on a fife: He looked again, and found it was A letter from his wife...

He thought he saw a Buffalo Upon the chimney-piece: He looked again, and found it was His sister's husband's niece...

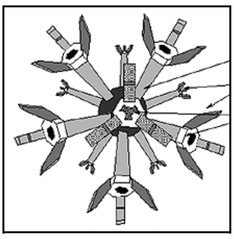
--Lewis Carroll, from "Sylvie and Bruno"

The concept of objects (or creatures) formed of "intelligent" polymorphic substances goes back at least to the 1930's. A stock character in the science fiction stories of the day was the amoeboid alien able to assume any shape, and to extrude specialized appendages at will. More recently the motion picture "Terminator 2" has popularized this notion of intelligent material. Nanotechnology will make intelligent material possible; but as usual, the truth will be stranger than the fiction. Not only can we build objects of intelligent material: we can embed them, along with "real" or pre-existing objects, in intelligent space! Intelligent material need not be polymorphic, and polymorphic material need not be intelligent. If you melt a piece of metal into a mold, it assumes a new shape. If you had an object that could perform the same transformation on command, it would be intelligent as well as polymorphic. There will exist technologies reflecting the entire spectrum between these extremes, starting with today's "memory plastics".

Using nanotechnology, we can design fully intelligent polymorphic material that consists, like your body, of trillions of microscopic machines. Like your cells, each machine will have a substantial local program and information storage, but will act in accordance with patterns of global information. Unlike your cells, they will be more quickly and more widely reprogrammable, adopt a wider array of functions, and look like spiders rather than jellyfish.

The Utility Fog The particular scheme for intelligent material I'm describing here is called Utility Fog. You can find a longer and more detailed exposition in a book edited by B.C. Crandall called Nanotechnology: Molecular Speculations on Global Abundance; the chapter entitled "The Stuff that Dreams are Made Of" is about Utility Fog. There's also a mention in Ed Regis' excellent book Nano. I invented Utility Fog in a typically serendipitous way. Virtually everyone working with nanotechnology has had ideas for a polymorphic material to make objects out of. But I was driving in to work one day and became conscious of my seat belt. I began wondering how good a seat belt you could make with nanotechnology.

One of my pet peeves about safe cars is the they're built to collapse in an accident; the crumpling of the structure gives you a longer deceleration path, which is what makes it safe. Suppose your vehicle looked more like a living room inside, with lots of space around you. It would be a lot more comfortable than a conventional car, and there would be room to decelerate without trashing the vehicle. Next thought: the cases they ship delicate equipment in, with form-fitting foam interiors. Suppose you could do a similar thing as a seat belt, in such a way that it didn't appear to be there when it wasn't needed. Once the basic notion was there, it remained only to figure out how to implement it. Utility Fog consists of a mass of tiny robots.



Unlike water fog, they do not float in the air but form a lattice by holding hands in 12 directions (corresponding to the struts in an octet truss). Each robot has a body that is fairly small compared to its armspread, and the arms are relatively thin. Each arm is telescoping, an action driven by a relatively powerful motor, and can be waved back and forth (2 more degrees of freedom) by relatively weak motors. One could of course design a Foglet (as the robots are called) with many fewer arms, e.g. 6, correspond to the easier-to-visualize cubic lattice.

The main reason for avoiding this is that that lattice is not isotropic; it responds quite differently to forces applied along an axis and those applied along a diagonal. Another is that the octet truss structure, which was invented by Buckminster Fuller, is such that it remains rigid even if all the arms are connected to the bodies by hinges; a rectangular truss would collapse, and therefore needs strong motors controlling the angle each arm makes with the body. Thus a 6-arm design would need 3 big motors per arm, for a total of 18. The octet structure needs only one big motor per arm, for a total of 12.

The arm-waving motors need only have enough power to position the arm itself, not to exert macroscopic forces throughout the structure. The other reason for so many arms is that you need some extra to allow robots to let go briefly to change neighbors, and still retain strength and connectivity in the structure. The grippers at the end of each arm have one degree of freedom, rotation, driven by a weak motor. The gripper has three fingers that when closed form an extension of the arm; when open they spread apart at a slight angle.

The grippers are solely for gripping the end of another arm, in a straight line. They are designed so that two arms approaching each other can be slightly off line and angle, and the coupling process is compliant. Once they are coupled, however, the resulting joint is straight and rigid. Coupling also makes power and communications connections between the two Foglets. The material properties of this mass depend on the programming of the robots.

The geometry is such that stresses in the material all appear as longitudinal forces along the arms. Each Foglet can sense the force along each arm, and do something depending on the magnitude and relation of those forces. If the program says, extend when the force is trying to stretch, retract when it is trying to compress, you have a soft material. If it says, resist any change up to a certain force, then let go, you have a hard but brittle material. If the programming says, maintain a constant total among the extension of all arms, but otherwise do whatever the forces would indicate; and when a particular arm gets to the end of its envelope, let go, and look for another arm coming into reach to grab; you have a liquid.

If you allow the sum of the arm extensions to vary with the sum of the forces on the arms, you have something that approximates a gas within a certain pressure range. Note that because the Foglets can use their own power to move or resist moving, the apparent density and viscosity of the fluid can be anything from molasses to near vacuum. Now you can begin to get cute. Run a distributed program that at a specified time, changes a certain volume from running water to running wood. A solid object would seem to appear in the midst of fluid. It can just as easily disappear.

Now fill your entire house with the stuff, running air in background mode. Have an operating system that has a library of programs for simulating any object you may care to; by giving the proper command you can cause any object to appear anywhere at any time. You could carry a remote control, which might happen to be shaped like a wand with a star on the end... More ambitiously, since you're embedded in the Fog, it can sense every detail of your bodily position. It forms a "whole-body dataglove", and you can control it with extremely subtle gestures. At the ultimate extreme, the Foglets can carry various special sensors ranging from simple electrodes with voltmeters to SQIDs and form an extremely high bandwidth polygraph.

With proper programming the Fog would almost be able to read your mind. This combination of extreme reactivity to control and virtually limitless creative and operational ability suggest a comparison with the Krell machine in "Forbidden Planet". Thus, here's a short list of the powers you'd have or appear to have if embedded in Fog: Creation: causing objects to appear and disappear on command. Levitation: causing objects to hover and fly around. Manipulation: causing forces (squeezing, hitting, pulling) on objects (real ones) at a distance. This includes a distance of inches; bend steel bars (real ones) like Superman. Teleportation: nearly any combination of telepresence and virtual reality between Fog-filled locations. Shape-shifting: Want to be a mouse? the Fog around you simulates very large feet, baseboards, etc, while your telepresence drives a mouse-sized and -shaped Fog program. Want to be the Statue of Liberty ... ?

How to Build a Fog

The only major breakthrough necessary to enable us to build the Fog world is nanotechnology itself. Assemblers, the sine qua non of nanotechnology, will require two major feats of molecular engineering: building molecular-sized, individually controllable, physical actuators, arms, motors, gears, sprockets, pulleys, and the like; and then building molecular sized computers to control them. Foglets need not be controllable to the same precision as true assemblers: They do not need to control chemical reactions at the atomic level. In fact, the only constraint on size is the ability to form a smooth enough surface to fool human senses.

The lower limit, based on designs from Nanosystems, is about a 1 or 2 micron body and 5 to 10 micron arms. The upper limit for completely undetectable granularity is probably about 50 to 100 microns, the range of diameter of human hair. If "super high fidelity" isn't critical, 1 mm Foglets would likely be able to do all the physical tasks of interest. (Note that the user, embedded in the Fog, is not really looking at it but at a synthetic image, probably generated by a pair of active holographic contact "lenses". I had originally designed the Foglets to be very small, so that they were less than the wavelength of light, in hopes that Fog could be transparent. After running the idea past several people, including Drexler, they managed to convince me that even Foglets of subluminal size, even though quite invisible individually, would cause enough scattering that a cloud of them would look like, surprise, a cloud.)

For applications not involving the embedding of humans, "Foglets" could be of any size consonant with the objects they had to manipulate. Imagine building a skyscraper by having a solid mass of robots each a foot or so in size, form an active scaffold in which beams and blocks and plates were moved around, hand over hand. Such "Foglets" could be built today; but they would be way too expensive for this kind of application.

Fog needs the self-reproducing productivity of nanotechnology to be economical. After all, filling an average house with even coarse 1 mm Foglets requires over a trillion of them, and for the hi-fi Foglets it's a quadrillion (1015) of them. For you to be able to afford them they'd better cost less than $0.00000000001 apiece. (If you were very very rich, you might be able to afford $0.000000001 Foglets.) What Foglets don't need is to be individually self-reproducing. Foglets, small though they may be on the macroscopic scale, are just a completely different kind of machine than a self-reproducing assembler.

Assemblers will be most efficient when they work in a vat of special precursor chemicals. This will also constitute a built-in safety factor against runaway replication: after all, you don't worry about baking yeast taking over the whole world when you make homemade bread; when it runs out of dough, it stops. Foglets operate out in the real world, with motion tolerances bigger than the assembler's entire working envelope. We'd expect Foglets to be built like virtually any other end product of a nano-based technology. There will in all likelihood not only be specialized Fog-making machines, and Fog-making-machine making machines, but Fog-making-machine-making-machine making machines.

The more specialized a production process is, the more efficient. The general-purpose assembler is a necessary bootstrap, but as nanotechnology matures it will engender longer and more complicated self-referential loops. The typical specialized nano-factory will be a breadbox to refrigerator-sized object, with literally trillions of parallel assembly lines converging in a tree-like structure to produce ever-larger subcomponents of the end product. For something as small as a Foglet the factory could be quite a bit smaller, of course. Problems and Non-problems The first question anyone asks about the Fog seems to be, "Won't it mutate into Grey Goo?" Then they learn that Foglets are not individually self-reproducing, and they say, "Oh." The templates, construction algorithms, and so forth for the Foglets will be in the Fog machine, where they can avail themselves of all the robustness, duplication, and error correction possible in a macroscopic machine.

The next question is "How do you breathe when the air is a solid mass of machines?" The answer is in several parts: First, the Foglets only occupy a small percentage of the actual volume of the air; they need lots of "elbow room" to move around easily. Thus there's plenty of air left to breathe. The other part of the question has several possible answers; Fog could enter your lungs, actively simulating the activity of unoccupied air (and scrub your lungs of air pollution, smoke, and whatnot with every breath), or form a Fog-free region around you into which fresh air was continually fanned.

What if the power fails and you are suddenly encased in solid unyielding material? If Foglets have a failsafe mode where they let go their neighbors and retract their arms as much as possible when they lose power, they form at first a super-heavy smoke or dust storm, and would ultimately pack down into something like clay. Not something to look forward to. Each Foglet would carry a certain amount of reserve power for normal operations (keeping a reserve locally saves a lot of power transmission, since energy flows into as well as out of the Fog in the course of everyday movements).

Furthermore, the Fog should carry along small special purpose batteries/fuel cells like raisins in a pudding. Even larger power generators could be carried along with each person so their personal cloud of Fog could be autonomously worn like a suit of clothes wherever they went. In a general power failure, general room Fog should retract to make thicker walls and ceiling (where it would lock in place), while your personal batch continued to help you cope.

"I have answered three questions, and that is enough," Said his father; "don't give yourself airs! Do you think I can listen all day to such stuff? Be off, or I'll kick you downstairs!" (ibid.)